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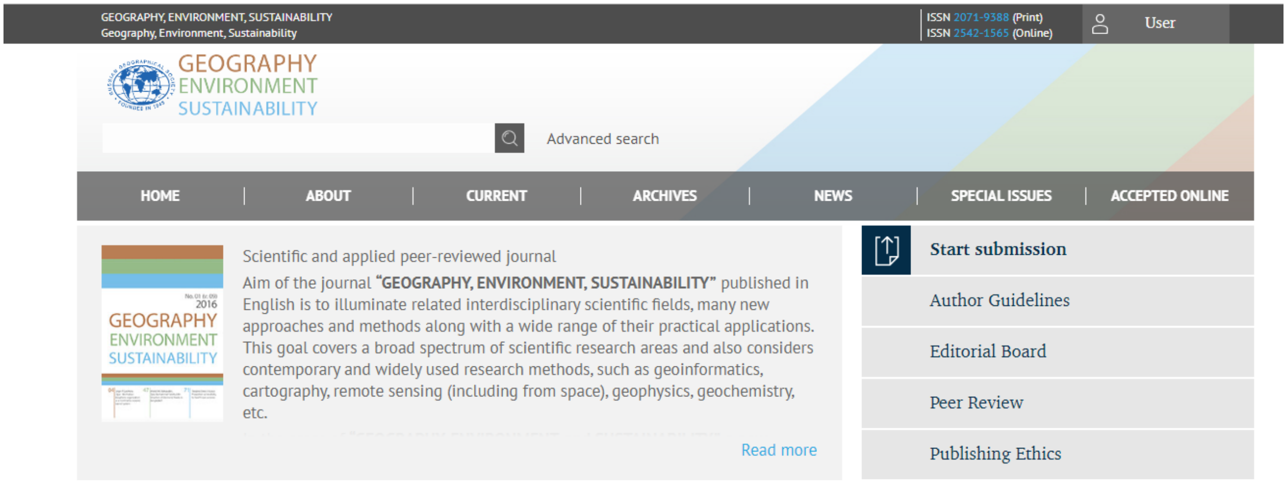

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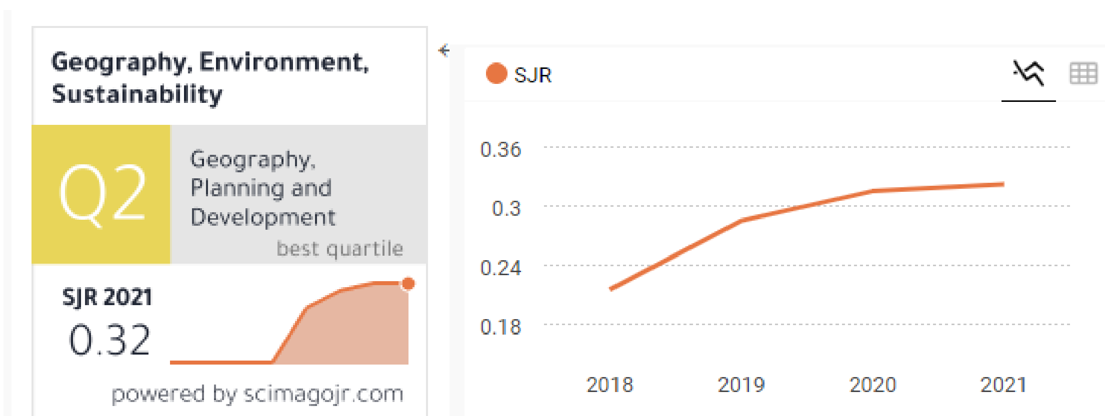

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1 message

Dr. Alexey A. Maslakov <no-reply@subs.elpub.ru> Thu, Sep 29, 2022 at 7:18 PM
Reply-To: "Dr. Alexey A. Maslakov" <ges-journal@geogr.msu.ru>
To: Abdul Malik <abdulmalik@unm.ac.id>

Dear Abdul Malik!

We have received the following manuscript to be considered for publication in the Geography, Environment, Sustainability journal:

"***CO2 UPTAKE IN ARTIFICIAL AND NATURAL MANGROVE FORESTS OF SOUTH VIETNAM***"

Abstract

Mangrove forests are one of the most productive and efficient long-term carbon sinks. Mangroves have experienced large-scale deforestation and conversion to other land uses, particularly in Southeast Asia. Present time the conservation of mangrove carbon stocks has been promoted in global climate negotiations due to their potential contribution to mitigating GHG emissions. However, uncertainty of estimating of CO2 fluxes remains recently due to geographical variability of mangrove forests and field data limitations. The paper presents the results of photosynthesis studies at the leaf level in-situ of seedlings of Rhizophora apiculata Blume, 1827 of natural and artificial origin. The research was carried out in a mangrove plantation located in the Can Gio Biosphere Reserve, located 50 km from Ho Chi Minh City (South Vietnam). The photosynthesis CO2 uptake was measured using a Portable Photosynthesis System LI-6800 (Li-Cor Inc., USA). The photosynthetic radiation is determining factor influencing the photosynthesis of the investigated seedlings of R. apiculata. Artificial seedlings growing in an open area had higher productivity and better photosynthetic performance. It was found that the obtained values of photosynthesis are distributed in three clearly marked zones, corresponding to the values of photosynthesis obtained in the pre-noon, noon and afternoon. The main inhibitory factor affecting the photosynthesis of R. apiculata is the disturbance of the water balance of the leaves. The optimum air temperature for the processes of photosynthesis in seedlings is (35 ± 2) °C. With an increase in the concentration of CO2 in the air, the intensity of photosynthesis also increases.

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To: Abdul Malik <abdulmalik@unm.ac.id>

Dear Abdul Malik!

Thank you for completing the review of the submission "*CO2 UPTAKE IN ARTIFICIAL AND NATURAL MANGROVE FORESTS OF SOUTH VIETNAM*," (ID 2515) for GEOGRAPHY, ENVIRONMENT, SUSTAINABILITY.

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Research paper

CO₂ UPTAKE IN ARTIFICIAL AND NATURAL MANGROVE FORESTS OF SOUTH VIETNAM

Nikolay G. Zhirenko [1,2], Van Thinh Nguyen [2], Juliya A. Kurbatova [1,*]
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ABSTRACT. Mangrove forests are one of the most productive and efficient long-term carbon sinks. Mangroves have experienced large-scale deforestation and conversion to other land uses, particularly in Southeast Asia. ~~Present time~~Currently, the conservation of mangrove carbon stocks has been promoted in global climate negotiations due to their potential contribution to mitigating GHG emissions. However, the uncertainty of estimating ~~of~~ CO_2 fluxes remains recently due to the geographical variability of mangrove forests and field data limitations. The paper presents the results of photosynthesis studies at the leaf level in-situ ~~of~~ seedlings of *Rhizophora apiculata* Blume, 1827 of natural and artificial origin. The research was carried out in a mangrove plantation located in the Can Gio Biosphere Reserve, ~~located~~ 50 km from Ho Chi Minh City (South Vietnam). The photosynthesis CO_2 uptake was measured using a Portable Photosynthesis System LI-6800 (Li-Cor Inc., USA). ~~The p~~Photosynthetic radiation is determining factor influencing the photosynthesis of the investigated seedlings of R. *apiculata*. Artificial seedlings growing in an open area had higher productivity and better photosynthetic performance. It was found that the obtained ~~values of photosynthesi~~photosynthesis values are distributed in three clearly marked zones, corresponding to the values of photosynthesis obtained in the pre-noon, noon, and afternoon. The ~~reserves of water~~water reserves consumed in the midday time did not fully recover from the seedlings in the afternoon. The main inhibitory factor affecting the photosynthesis of R. apiculata (if we do not take into account PAR) is the disturbance of the water balance of the leaves. The optimum air temperature for the processes of photosynthesis in seedlings is (35 ± 2) °C. With an increase in the concentration of CO_2 in the air, the intensity of photosynthesis also increases.

KEYWORDS: *Rhizophora apiculata*, air temperature, CO_2 concentration, diurnal dynamics, intensity of photosynthesis, light response curve

CONFLICTS OF INTEREST

The authors reported no potential conflicts of interest.

INTRODUCTION

Mangrove forests are one of the unique forest ecosystems. They are an important part of tropical coastal ecosystems. Being of great ecological importance, mangroves also fulfill protective and economic functions (Donato et al. 2011; Hogarth 2007; Hogarth 2008; Simard et al. 2019; Saintilan et al. 2020).

However, the degradation of mangrove ecosystems is currently being observed (Alongi 2002; Valiela et al. 2001; Nguyen 2000). This is due both to economic activity, which mainly consists of the deforestation of these forests (Luong 2014) and to the ongoing global warming (Desherevskaya et al. 2013), which results in both sea-level rise and the associated flooding of mangrove forests, as well as the drying up of individual mangrove ecotopes (FAO 2007; Simard et al. 2019).

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Thus, the study of mangrove forests is of undoubted interest to scientists. One of the main directions of such research is research related to the study of the physiological characteristics of mangroves. The most significant of these are studies related to their gas exchange (Clough 1997). Nevertheless, despite sufficient knowledge in this area of research, many questions remain in the shadows. In particular, this applies to the mangroves of Vietnam.

According to our estimates, one of the most common tree species in the mangrove forests of South Vietnam is *Rhizophora apiculata* Blume, 1827. This species is widely used in reforestation activities (Hogarth 2007). Forming grandiose plantations due to its stilted roots, *R. apiculata* plays an important role in the ecology of mangrove forests (Thongjoo et al. 2018; Wenfang et al. 2020). Of undoubted interest is the fact that *R. apiculata* belongs to plants with C4 photosynthesis, which allows the plant to better adapt when growing in conditions of high temperatures and lack of water (Ehleringer and Björkman 1977; Slack and Hatch 1967). Therefore, it is not accidental that many researchers pay attention to this species (Christensen 1978; Ong et al. 1995).

Our previous studies carried out on mature *R. apiculata* trees showed that photosynthesis depression in these trees began to manifest itself at noon and was observed until the end of daylight hours (Đỗ Phong Lưu et al. 2021). In accordance with this, we put forward a hypothesis that the parameters characterizing the photosynthetic abilities of *R. apiculata* should differ at different times of the day. We did not find any studies confirming or refuting our assumption. We also assumed that the indicated parameters should also differ in plants growing in different conditions.

In accordance with the hypothesis put forward, the purpose of the work was determined: to study the daily variability of the parameters of the photosynthetic ability of *R. apiculata* seedlings of artificial and natural origin.

In accordance with the purpose of the work, the following tasks were set: to obtain daily dynamics of the intensity of photosynthesis for seedlings of artificial and natural origin, to model the response curves of photosynthesis to light according to the Michaelis-Munten equation (1), to obtain the dependence of photosynthesis on temperature and CO_2 concentration in the air, to conduct analysis of the obtained results.

This article presents the results of our research related to the study of the photosynthetic exchange of CO_2 at the leaf level *in-situ* of seedlings of *R. apiculata* of natural and artificial origin. These results can be used to recalculate photosynthesis at the leaf level, down to the planting level. Also, the results obtained will contribute to predicting the growth of plants of this species both in the current period of time and in the future in connection with global climatic changes. In practice, the research results will be useful in the development of reforestation measures.

MATERIALS AND METHODS

Study site, plant material and growing conditions

The research was carried out in July 2020 in a mangrove plantation located in the Can Gio Biosphere Reserve, located 50 km from Ho Chi Minh City (10°28′36″N, 106°54′17″E) (South Vietnam). Seedlings of *Rhizophora apiculata* Blume, 1827, about 5 years old, of artificial and natural origin, were chosen as the test material.

Artificial seedlings grew in an open area and were intended for reforestation activities (Fig. 1a). The number of studied seedlings n = 27, their average height h = 57 cm (Standard Deviation, *SD* = 7 cm), the average number of leaves per seedling N = 35 (*SD* = 16).

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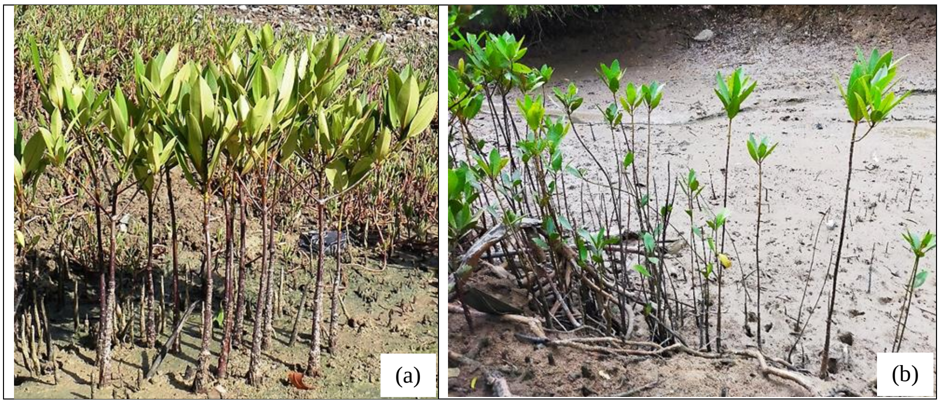

Fig. 1. Studied seedlings of *R. apiculata* of artificial (a) and natural (b) origins

Natural seedlings grew along the edge of the water channel on its northern side (Fig. 1b). The seedlings were formed as a result of the germination of floating fruits that were washed ashore. At noon, the seedlings were shaded by the trees and shrubs growing behind them. Seedling parameters: n = 14, h = 88 cm (*SD* = 8 cm), N = 10 (*SD* = 5).

Twice a day, both sites were flooded with water as a result of sea tides.

Measurement of photosynthetic gas exchange and experimental design

Photosynthesis processes were considered from the standpoint of CO_2 gas exchange. The rate of photosynthesis (photosynthesis) was measured using a Portable Photosynthesis System LI-6800 (Li-Cor Inc., USA). For artificial illumination of the investigated part of the sheet, a 3 × 3 cm light source was used, supplied by the LI-6800 manufacturer as an addition to the device. The emission spectrum of the light source consists of red (λ = 660 nm) and blue (λ = 453 nm) colors. When using it, the object was illuminated with light, consisting of red and blue colors in a ratio of 9: 1. During measurements under natural light, photosynthetically active radiation (PAR) was measured using a sensor located in the LI-6800 measuring chamber.

During measurements, the required microclimate parameters were set in the LI-6800 measuring chamber - object illumination, air temperature and humidity, and CO_2 concentration.

For the study, we used the formed intact leaves, as a rule, located on the penultimate node of the shoot. The measurements were carried out in the middle part of the leaf, bounded by the frame of the LI-6800 measuring chamber with an aperture of 3x3 cm. Current measurements of photosynthesis were carried out on 2-4 randomly selected seedlings. To construct the diurnal graphical dependencies, the average values of the measured values were used.

Studies of the dependence of photosynthesis on temperature were carried out on artificial seedlings. During measurements, the following microclimate parameters were set in the LI-6800 measuring chamber: illumination 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, CO_2 concentration 400 $\mu mol \cdot mol^{-1}$, humidity ~ 60%. The measurements were carried out in an automatic mode in the temperature range from 24 to 46 °C.

Studies of the dependence of photosynthesis on CO_2 concentration were also carried out on artificial seedlings. During measurements, the following microclimate parameters were set in the LI-6800 measuring chamber: illumination 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, temperature 30 °C, humidity ~ 70%. The measurements were carried out in an automatic mode in the CO_2 concentration range from 350 to 1000 $\mu mol \cdot mol^{-1}$ with a step of 50 $\mu mol \cdot mol^{-1}$.

The work used meteorological data obtained from a meteorological station located on the territory of the reservefrom a meteorological station located on the reserve's territory.

Diurnal curves of photosynthesis and PAR

The data for plotting the diurnal dynamics of photosynthesis and PAR were obtained over two days: July 4, 2020, from 15:00 to 19:00 and on July 27, 2020, from 05:00 to 14:30. The total solar radiation these days differed by 6% (the cloudiness on July 4, 2020, in the first half of the day was slightly higher). The average air temperature during the daylight hours on July 4, 2020, was 34 °C, on July 27, 2020 - 36 °C.

The measurements were carried out with an interval of ~20 min with the following microclimate parameters in the LI-6800 measuring chamber: CO_2 content 400 μmol·mol^{-1}, humidity ~65%, temperature ~32 °C.

Light-response curves

The mathematical description of the curves of the light response of photosynthesis was based on the Michaelis - Munten equation (Michaelis and Muenten 1913). We used this equation in a modified form (Kaipiainen 2009):

$$A=A_m \cdot Q/(Q+K_M)+A_d \quad (1),$$

where A is the intensity of photosynthesis, μmol·m^{-2}·s^{-1}; A_m - is the maximum intensity of photosynthesis, μmol·m^{-2}·s^{-1}; Q - PAR, μmol·m^{-2}·s^{-1}; A_d - respiration rate at Q = 0, μmol·m^{-2}·s^{-1}; K_M - Michaelis constant (K_M is numerically equal to PAR, at which the intensity of photosynthesis is half of the maximum $A = 0.5A_m$). The values of this constant are often used by researchers when comparing the physiological characteristics of plants (Hieke et al. 2002). According to (1), the light compensation point (*LCP*) was determined, μmol·m^{-2}·s^{-1}, which shows at what intensity of PAR photosynthesis becomes zero.

To assess the efficiency of photosynthesis, we propose to use the slope of the tangent *a* (italic font) to the function curve of (1) at the point corresponding to K_M. From a physical point of view, this coefficient reflects the rate of change in the intensity of photosynthesis with a change in PAR by one unit.

Statistical analysis

Data processing was carried out using the MS Excel "Descriptive statistics" package (p <0.05). The degrees of association of the studied datasets were determined using Pearson's correlation coefficients, *k*. The parameters of equation (1) were selected using the MS Excel package "Parameters of the solution search" (the limiting number of iterations is 100, the relative error is 0.00001, the permissible deviation is 5%, the convergence is 0.0001). The slope *a* of the tangent, the coefficients of the equation for this tangent, as well as the extremum points of the graphical dependencies were determined using differentiation methods. The total values of the investigated quantities were determined by the integration method. Graphing was carried out using the MS Excel environment.

RESULTS

Diurnal dynamics of photosynthesis and PAR

Fig. 2 shows the daily dynamics of the intensity of photosynthesis and PAR, obtained as a result of measurements on seedlings of artificial origin.

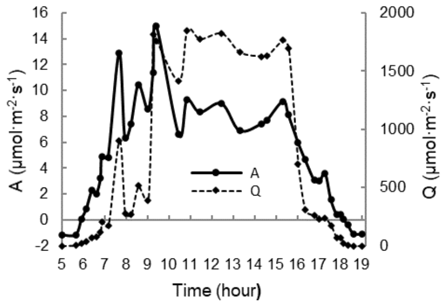

Fig. 2. Daily dynamics of the intensity of photosynthesis – *A*, and PAR – *Q*, of artificial seedlings

The dependences of photosynthesis and PAR for these seedlings are characterized by a good degree of the association during the day, *k* = 0.78. On the other hand, when analyzing the degree of association of these quantities in the pre-noon (from 06:00 to 09:30), noon (from 09:30 to 15:30), and afternoon (from 15:30 to 18:30), the following *k* values were obtained: 0.85, 0.50 and 0.87, respectively.

The total PAR for artificial seedlings was 46.9 ± 2.4 mol·m^{-2}. In the first half of the day (up to ~ 12 h), it was 24.2 ± 1.3 mol·m^{-2}, in the second - 22.8 ± 1.2 mol·m^{-2}.

The total CO_2 exchange for these seedlings was 0.304 ± 0.016 mol·m^{-2}. However, both in the first half of the day (up to ~ 12 h) and in the second, it was the same and amounted to 0.154 ± 0.008 and 0.151 ± 0.008 mol·m^{-2}, respectively.

Fig. 3 shows the daily dynamics of the intensity of photosynthesis and PAR, obtained as a result of measurements on seedlings of natural origin.

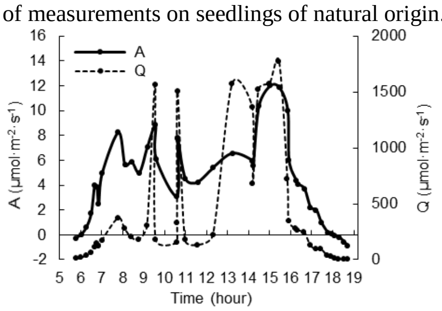

Fig. 3. Daily dynamics of the intensity of photosynthesis - *A*, and PAR - *Q*, seedlings of natural origin

The dependences of photosynthesis and PAR for these seedlings are also characterized by a good degree of the association during the day, *k* = 0.78. When analyzing the degree of association of these dependencies in the pre-noon, noon, and afternoon hours, the following *k* values were obtained: 0.96, 0.77, and 0.90, respectively.

The total PAR for seedlings of natural origin was 24.2 ± 1.3 mol·m^{-2}. In the first half of the day (up to ~ 12 h), it was 5.8 ± 0.3 mol·m^{-2}, in the second - 18.4 ± 1.0 mol·m^{-2}.

The total CO_2 exchange for these seedlings was 0.241 ± 0.013 mol·m^{-2}. In the first half of the day (up to ~ 12 h), it was 0.103 ± 0.006, in the second - 0.138 ± 0.007 mol·m^{-2}.

Light-response curves

Figure 4 shows the values of photosynthesis depending on PAR, measured on seedlings of artificial (Fig. 4a) and natural (Fig. 4b) origin. The figures also show the curves approximating these values, constructed according to (1) for the values obtained in the pre-noon (curves 1) and in the afternoon (curves 2) and tangents to these curves at the points corresponding to the K_M values. Photosynthesis values obtained in the pre-noon time are indicated by markers in the form of circles, at noon - in the form of triangles, in the afternoon - in the form of open circles.

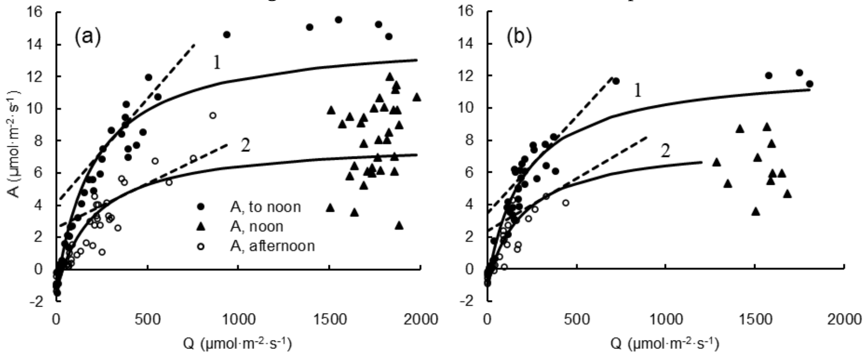

Fig. 4. Dependences of the intensity of photosynthesis - *A*, on PAR - *Q*, obtained on seedlings of artificial (a) and natural (b) origins. These figures also show the curves approximating these values, constructed according to (Equation 1) for the values obtained in the pre-noon (curves 1) and in the afternoon (curves 2) and tangents to these curves at the points corresponding to the K_M values

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The indicators characterizing the photosynthetic characteristics of seedlings obtained according to (1), as well as the R^2 values for the curves plotted and the number of measurements n, are summarized in Table 1.

Table 1. Indicators characterizing photosynthetic characteristics of seedlings.

Index	Seedlings of artificial origin		Seedlings of natural origin	
	Pre-noon time	Afternoon time	Pre-noon time	Afternoon time
R^2	0.97	0,90	0.95	0,89
n	124		94	
A_m, μmol·m^{-2}·s^{-1}	16.0	9.5	13.5	8.9
a	0.013	0.006	0.012	0.007
K_M	202.5	202.7	204.2	204.6
A_d, μmol·m^{-2}·s^{-1}	-1.5		-1.0	
LCP, μmol·m^{-2}·s^{-1}	21.0	38.0	16.3	25.9

Dependence of photosynthesis on temperature and CO_2 concentration

The obtained values of the intensity of photosynthesis for seedlings of artificial origin, as a function of the temperature T of the air surrounding the leaf, are approximated by a quadratic equation (R^2=0.97, n=20):

$$A(T) = -0.0889T^2+6.2453T-100.84 \quad (2).$$

The extremum of this function corresponds to a value of T = 35 °C. Therefore, taking into account measurement errors, the optimal temperature for photosynthesis of *R. apiculata* seedlings is T_{opt} = (35 ± 2) °C.

The dependence of the intensity of photosynthesis of seedlings on the concentration of CO_2 in the air is described by a linear equation (R^2=0.95, *n*=13):

$$A(CO_2) = 0.0056CO_2+2.62 \quad (3).$$

DISCUSSION

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Effect of PAR on photosynthesis

The diurnal dynamics of the intensity of photosynthesis of seedlings of artificial origin (Fig. 2) show the following distinctive patterns:

1) an increase in photosynthesis to maximum values in the pre-noon time, up to 09:30, in proportion to an increase in PAR (*k* = 0.85);

2) a decline in photosynthesis from maximum values to values corresponding on average to 8.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (SD = 2.4 $\mu mol \cdot m^{-2} \cdot s^{-1}$), and the exit of the photosynthesis curve to a kind of plateau at noon, from 09:30 to 15:30, with a weak dependence of photosynthesis on PAR (*k* = 0.50);

3) a decline in photosynthesis in the afternoon, from 15:30, in proportion to a decrease in PAR (*k* = 0.87);

4) negative values, indicating the processes of respiration occurring in the leaf, at night.

It is interesting to note that the same diurnal dynamic was obtained for the light leaves of *Rhizophora mucronata* Poir. growing in Indian red mangroves (Kumar et al. 2017).

In order to give a more detailed interpretation of the listed patterns, let us turn to the dependences of photosynthesis on PAR (Fig. 4a) and indicators characterizing the photosynthetic characteristics of seedlings (Table 1).

As can be seen from Fig. 4a, the markers representing the obtained photosynthesis values are distributed in three clearly marked zones: 1 - in the zone corresponding to the photosynthesis values obtained in the pre-noon (markers in the form of circles); 2 - in the zone corresponding to the values obtained at noontime (triangular markers); 3 - in the zone corresponding to the values obtained in the afternoon (markers in the form of open circles).

The curves plotted according to (1) for the photosynthesis values obtained in the pre-noon and afternoon (Fig. 4a) have a high degree of association (Table 1). The K_M coefficients characterizing the physiological characteristics of plants are approximately the same, which is obvious since we examined plants of the same type. However, the maximum intensity of photosynthesis, A_m, in seedlings in the pre-noon time was significantly higher than in the afternoon. The same applies to the slopes *a*. Thus, in artificial seedlings, the efficiency of photosynthesis in the pre-noon time was 2.2 times higher than in the afternoon.

On the other hand, the *LCP* for these seedlings in the afternoon was 1.8 times higher than that in the pre-noon. That is, in the afternoon, at a PAR of 38.0 $\mu mol \cdot m^{-2} \cdot s^{-1}$, the absorption of CO_2 by the leaf was compensated by its release. Such processes are caused by respiration, as a rule, associated with metabolic processes occurring in the leaf.

In addition to the above, it can be noted that, according to Figures 2 and 4a, the saturation of photosynthesis for these seedlings occurs when the PAR is about 1800 $\mu mol \cdot m^{-2} \cdot s^{-1}$.

A similar pattern in the dynamics of photosynthesis, indicating its different behavior in the pre-noon and afternoon, was not identified by the authors of this work in similar studies. However, it should be noted that the authors of the work (Ball et al. 1997), when conducting similar studies, noted a very large scatter of data. In our studies, with the exception of midday measurements, this was not noted.

The daily dynamics of photosynthesis in seedlings of natural origin (Fig. 3), in general, is characterized by the same regularities as in seedlings of artificial origin. Distinctive features of this dynamics are somewhat large values of *k* obtained before and afternoon (0.96 and 0.90), as well as the presence of a relationship between photosynthesis and PAR at noon (k = 0.77).

A similar situation emerges when analyzing the features of photosynthesis of seedlings according to Figure 4b - the obtained values of photosynthesis are also distributed in the three zones indicated above.

The plotted curves (1) for the values of photosynthesis obtained before and afternoon also have a high degree of association (Table 1). The K_M coefficients are approximately the same. The maximum intensity of photosynthesis, A_m, in seedlings in the pre-noon time is significantly higher than in the afternoon. The same applies to the slopes *a*. Thus, in seedlings of natural origin, the efficiency of photosynthesis in the pre-noon time was 1.7 times higher than in the afternoon. The *LCP* for these seedlings in the afternoon was 1.6 times higher than that in the pre-noon time. In the afternoon, *LCP* was 25.9 μmol·m^{-2}·s^{-1}.

Summarizing what has been said, we can present a comparative analysis of the characteristics of the growth of seedlings of artificial and natural origin.

On the one hand, these seedlings have similar characteristics. Thus, the diurnal dynamics of seedlings is characterized by an increase in photosynthesis in the pre-noon and a decrease in photosynthesis in the afternoon, with strong degrees of connection with PAR (Fig. 2, 3). The obtained values of photosynthesis are distributed in three clearly marked zones, corresponding to the values of photosynthesis obtained in the pre-noon, noon and afternoon (Fig. 4a, 4b). Photosynthesis values obtained in the pre and afternoon time are described with a high degree of association (1).

Slope coefficients *a* obtained for seedlings during pre-noon and during the afternoon are identical (Table 1). Accordingly, the efficiency of photosynthesis during pre-noon and during the afternoon is approximately the same and during pre-noon, it is higher than during the afternoon. K_M coefficients for seedlings are approximately the same. *LCP* for seedlings in the afternoon was higher than that during pre-noon.

On the other hand, the seedlings under consideration also have distinctive characteristics. So, at noon, photosynthesis in seedlings of artificial origin was more stochastic, while in seedlings of natural origin, there is a connection between photosynthesis and PAR. Further, the maximum values of photosynthesis, A_m, for seedlings of artificial origin, both during pre-noon and afternoon, were significantly higher than those of seedlings of natural origin. This is primarily due to different lighting conditions of seedlings: the total PAR for artificial seedlings was 46.9 ± 2.4 mol·m^{-2} (in the first and second half of the day it was on 23.5 ± 1.3 mol·m^{-2}), while for seedlings natural origin - 24.2 ± 1.3 mol·m^{-2} (in the first half of the day it was 5.8 ± 0.3 mol·m^{-2}, in the second - 18.4 ± 1.0 mol·m^{-2}).

Accordingly, the total CO_2 gas exchange for artificial seedlings was 0.304 ± 0.016 mol·m^{-2} (in the first and second half of the day it was the same and amounted to on 0.153 ± 0.008 mol m^{-2}), whereas, for seedlings of natural origin, the total CO2 exchange was 0.241 ± 0.013 mol·m^{-2} (in the first half of the day it was 0.103 ± 0.006, in the second - 0.138 ± 0.007 mol·m^{-2}).

The saturation of photosynthesis for these seedlings (Fig. 3 and 4b) occurs when PAR equals about 1500 μmol·m^{-2}·s^{-1}.

It should be noted here that the saturation values of photosynthesis obtained by us, both for artificial seedlings and for seedlings of natural origin, are fundamentally different from those presented in (Ball et al. 1997) that was amounting to about 400 μmol·m^{-2}·s^{-1}.

Thus, seedlings of artificial origin had higher productivity, and this was determined, first of all, by the amount of PAR supplied to the plants. Higher metabolic processes occurring in the leaves of plants of seedlings of artificial origin are also indicated by higher values of *LCP* and A_d (Table 1).

Naturally, the considered physiological parameters affected the morphological characteristics of the seedlings. Thus, the average number of leaves on a seedling of artificial origin is N = 35 (SD = 16), while on a seedling of natural origin - N = 10 (SD = 5). However, such a significant difference in the number of leaves on seedlings was to some extent compensated by the height - seedlings of natural origin were 1.5 times higher.

Effect of temperature and CO_2 concentration on photosynthesis

Analysis (2) showed that the optimal air temperature for photosynthesis of *R. apiculata* is T_{opt} = (35 ± 2) °C. It can be noted here that our similar studies on an adult tree *R. apiculata* of natural origin gave the same result (Đỗ Phong Lưu et al. 2021). According to (Ball et al. 1997), this figure is approximately 38 °C. However, the authors noted a large scatter of data and, unfortunately, do not indicate the amount of error in the determined value. In another work (Okimoto et al. 2013), two values of this temperature are given: 33 °C and 26 °C. Because the authors used similar equipment to carry out their studies, taking into account the error, we can say that the first temperature coincides with T_{opt}. Thus, the deviation of the air temperature from T_{opt}, both to a lower and to a higher side, causes a decrease in photosynthesis in *R. apiculata* (Sage and Kubien 2007).

The average air temperature during measurements at noon was 37.2 °C (SD = 1.0 °C). However, such temperatures could cause a decrease in photosynthesis by only 0.1%. On the other hand, we did not measure the temperature of the leaves, which, as a result of exposure to direct solar radiation (Fig. 1a and 2), could be quite high. High leaf temperatures inhibit photosynthesis. In addition, plants could experience a water shortage. For example, our studies related to the moisture content of leaves in relation to their absolutely dry weight on an adult *R. apiculata* tree showed that from 08:50 to 15:20 the leaves were losing 34% of moisture.

It is possible that in different leaves of seedlings, water deficiency manifested itself in different ways with corresponding changes in photosynthesis. At least, this hypothesis can explain the stochastic distribution of the values of photosynthesis in artificial seedlings at noon.

In contrast to this, in seedlings of natural origin, the presence of a connection between photosynthesis and PAR was noted at noon. This is due to the fact that these seedlings in the midday time were shadowed by the trees and shrubs growing behind them (Fig. 1b and 3). As a result, the leaves of these seedlings were exposed to significantly less overheating and so experienced less water deficit.

Based on what has been said, we can make the following assumption. In the studied seedlings, the water consumed during midday time was not completely restored afterwards. This can explain the significantly lower photosynthetic parameters observed in seedlings during afternoon (Table 1) than during pre-noon. This assumption is confirmed by the conclusions made in the work (Kumar et al. 2017).

The dependence of the intensity of photosynthesis of *R. apiculata* on the concentration of CO_2 in the air is described by (3). It follows from this equation that with an increase in CO_2 concentration, photosynthesis naturally increases. An increase in the growth of *R. apiculata* seedlings at increased CO_2 concentration in the air is noted in in (Eong et al. 1997; Kumar et al. 2017).

The presented dependences of photosynthesis on temperature and CO_2 concentration find their confirmation also in a number of works related to the study of the effect of elevated temperature and CO_2 concentration, simulating global warming, on photosynthesis of C4 plants (Alberto et al. 1996; Ghannoum et al. 2000; Read and Morgan 1996; Morgan et al. 1994). In our case, for example, if we consider the most optimistic forecasts associated with an increase in the concentration of CO_2 in the air in the next decade from 412 ppm to 460 ppm (and this concentration is already observed over cities), then the intensity of photosynthesis in the studied seedlings will increase by about 6%. This trend will be one of the tools for stabilizing the climate on Earth.

CONCLUSIONS

Commented [AM6]: I suggest the conclusions offer a clear interpretation of the findings in a way that emphasizes the importance of your study or describes the consequences of your arguments by justifying to your readers why your arguments matter. A conclusion must be broader and more comprehensive than specific or limited findings, and in the same vein, several findings may be combined into a single conclusion.

1. The determining factor influencing the photosynthesis of the investigated seedlings of *R. apiculata* is PAR. This determines the higher productivity of artificial seedlings in comparison with natural seedlings.

2. The obtained photosynthesis values are distributed in three clearly marked zones, corresponding to the photosynthetic values obtained in the pre-noon, noon and afternoon.

3. In the studied seedlings, the water consumed in the midday time was not completely restored afterwards. As a result, the photosynthetic parameters of the seedlings in the pre-noon were significantly higher than in the afternoon.

4. The main inhibiting factor affecting the photosynthesis of *R. apiculata* (if we do not take into account PAR) is the disturbance of the water balance of the leaves (lack of water).

5. The optimum air temperature for the processes of photosynthesis in *R. apiculata* seedlings is (35 ± 2) °C.

6. With an increase in the concentration of CO_2 in the air, the intensity of photosynthesis in *R. apiculata* naturally increases.

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